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La Yeguada volcanic complex, western Panama : an assessment of the geologic hazards using new $^{40}AR/^{39}Ar$ Ages

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La Yeguada Volcanic Complex, Western Panama: An Assessment of the Geologic Hazards Using New $^{40}Ar/^{39}Ar$ Ages

By

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A Report
Submitted in partial fulfillment of the requirements for the degree of
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This report, “La Yeguada Volcanic Complex, Western Panama: An Assessment of the Geologic Hazards Using New $^{40}Ar/^{39}Ar$ Ages”, is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN GEOLOGY

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La Yeguada Volcanic Complex, Western Panama: An Assessment of the Geologic Hazards Using New $^{40}Ar/^{39}Ar$ Ages

Karinne L. Knutsen

Abstract

La Yeguada volcanic complex is one of three Quaternary volcanic centers in Panama, and is located on the southern slope of the Cordillera Central mountain range in western Panama, province of Veraguas. To assess potential geologic hazards, this study focused on the main dome complex near the village of La Laguna and also examined a cinder cone 10 km to the northwest next to the village of Media Luna. Based on newly obtained $^{40}Ar/^{39}Ar$ ages, the most recent eruption occurred approximately 32 000 years ago at the Media Luna cinder cone, while the youngest dated eruption at the main dome complex occurred 0.357 ± 0.019 Ma, producing the Castillo dome unit. Cerro Picacho is a separate dome located 1.5 km east of the main complex with a date of 4.47 ± 0.23 Ma, and the El Satro Pyroclastic Flow unit surrounds the northern portion of the volcanic complex and has an age of 11.26 ± 0.17 Ma. No Holocene (10 000 years ago to present) activity is recorded at the La Yeguada volcanic complex and therefore, it is unlikely to produce another eruption. The emergence of a new cinder cone is a possibility, but the associated hazards tend to be low and localized, and this does not pose a significant threat to the small communities scattered throughout the area. The main geologic hazard at the La Yeguada volcanic complex is from landslides coming off the many steep slopes.

1. Introduction

Volcanic hazards in Panama are focused on three volcanic centers thought to be potentially active (Figure 1), but these volcanoes are not well studied. During the period of Aug 2006 to Sep 2007, the author Knutsen lived in Chitra (8° 31.657'N, 80° 54.418'W), then lived in Las Sabanas to the east (8° 35.024'N, 80° 40.742'W) between Oct 2007 to Mar 2008. This enabled new sampling and field inspection of the La Yeguada volcanic complex. Since previous dating work here (Defant et al, 1991, Richerson, 1990), suggested an extremely wide (possibly unlikely) range of dates which spanned all the way from Miocene to Holocene (23 million to 10 000 years ago), and because of concern about potential volcanic hazards, samples were dated by Argon analysis ($^{40}Ar/^{39}Ar$), which support the previous wide range of ages for the complex but also help us conclude that the potential hazards are minimal at this time.

2. Regional Setting

Panama is a product of the complex interaction of the Caribbean, Cocos, Nazca and South American plates (Hoernle, 2002, Coates, 1997), with the subduction of the Nazca plate still occurring beneath the Panamanian portion of the Caribbean plate. Forming the isthmus between Central and South America, the land mass of Panama is a land bridge for migrations of species, and its formation blocked the mingling of the Pacific and Caribbean/Atlantic waters, changing global ocean circulation and weather patterns.

La Yeguada Volcanic Complex (LYVC) is located in western Panama (8° 27.936'N, 80° 49.160'W) on the southern, Pacific slope of the Cordillera Central; the mountain range that forms a backbone through western Panama. The Cordillera Central is comprised of Neogene (23 – 2.6 million years ago (Ma)) volcanics (Coates, 2005, De Boer, 1988), and the younger peaks, less than 5 Ma, have come through these older deposits, and are all located on the southern slopes of the Cordillera Central (Defant et al, 1991). In the Veraguas Province, Calobre District, La Yeguada (sometimes referred to as Chitra-Calobre) is one of three volcanoes in Panama that are considered potentially active (Smithsonian Global Volcanism Program, Simkin & Siebert, 1994), the other two are Volcán Barú near the Costa Rica border and El Valle to the east (See Figure 1).

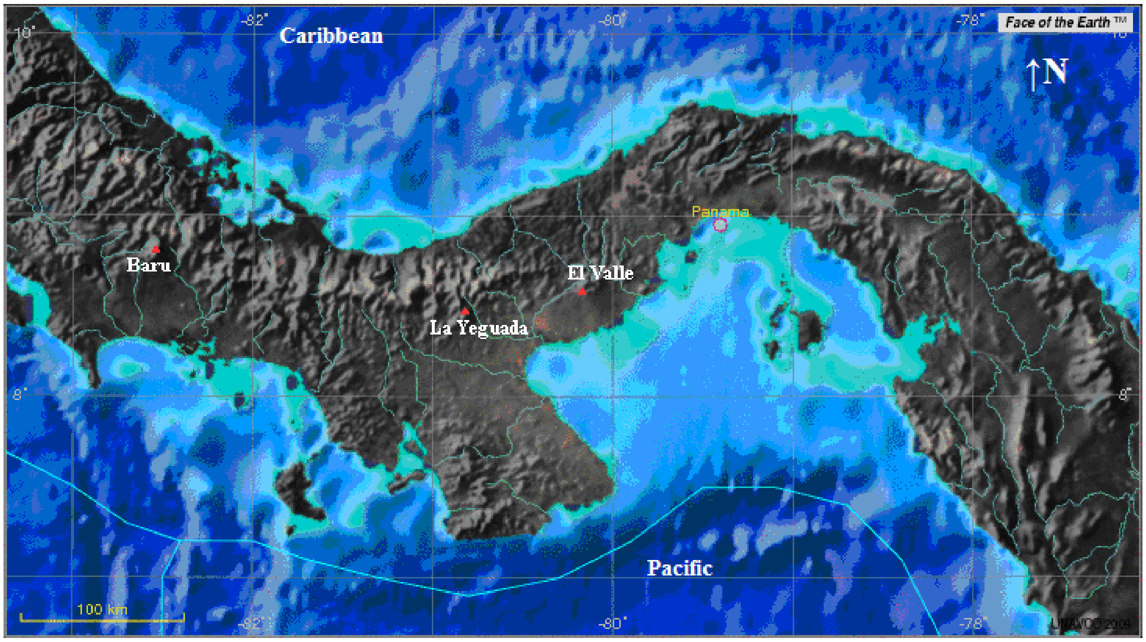


Figure 1. Map of Panama showing the three Quaternary volcanic centers and Panama City. From left to right: Volcán Barú, La Yeguada and El Valle. From Jules Verne Voyager (http://jules.unavco.org/Voyager/Earth).

The La Yeguada volcanic complex is comprised of three separate domes forming a circle, Cerro Castillo to the west and south, Cerro Novillo to the east and Cerro Corero to the north. On the geologic map (See Figure 2) Cerro Corero is its own unit (Tco), while Cerro Novillo and Cerro Castillo are both part of the Castillo unit (Tca). The highest peak is Cerro Castillo at 1 297 m. The Lake La Yeguada and the town La Laguna lie on the western edge of the volcanic complex, and the elevation in the town is 650 m (See Figure 2). A preliminary map of the complex was created by Richerson (1990), who named several units of the complex. His subdivisions have been kept here, so that the data he supplied on chemical composition and petrography/mineralogy can readily be part of the interpretive information.

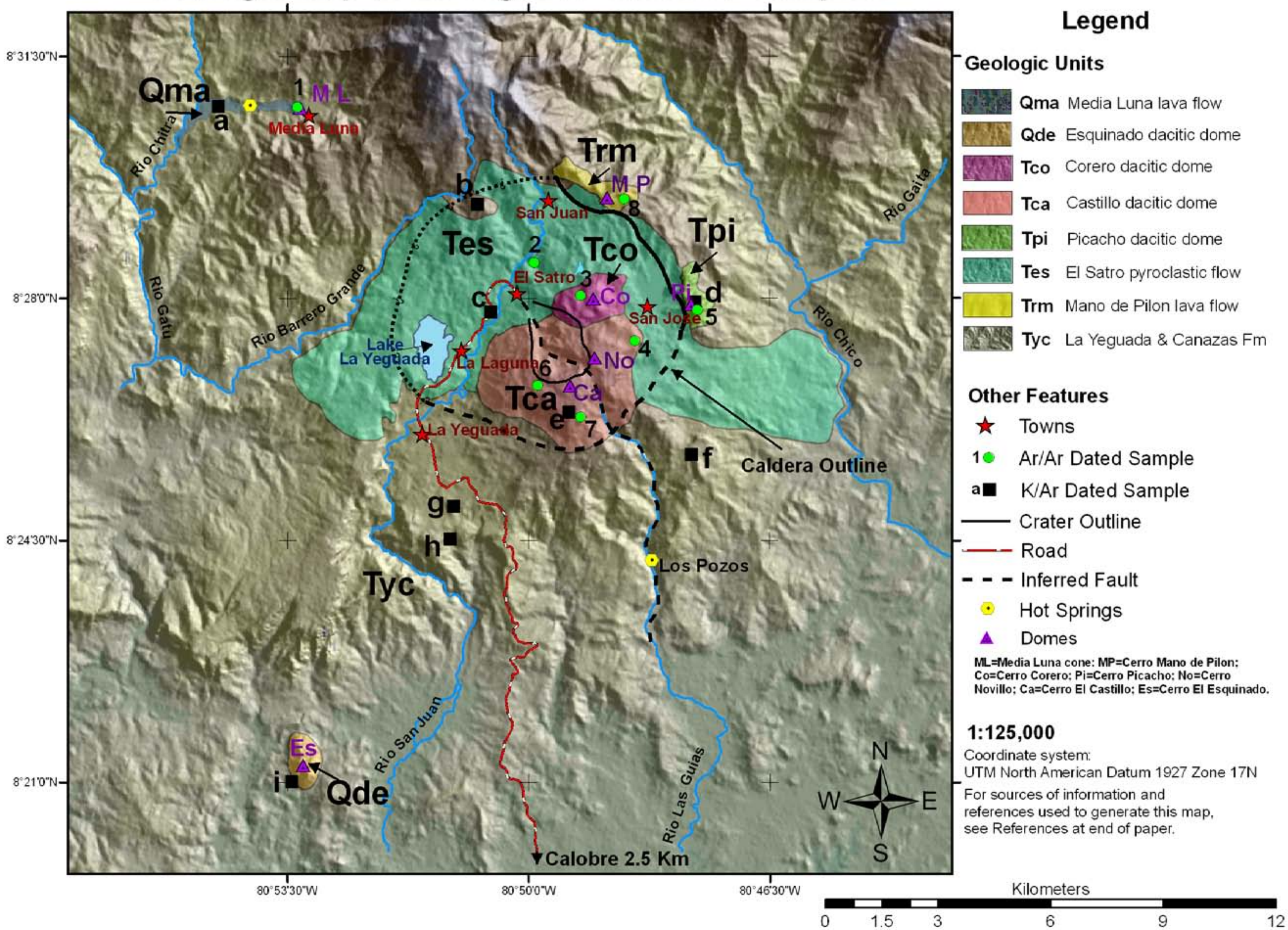
There are small hot springs and seeps located in the area; along the Quebrada Media Luna River 1.3 km west of the cinder cone; and Los Pozos, in the Rio Las Guias, is approximately 4 km south of the LYVC (See Figure 2). In La Laguna people mentioned that along the northeastern flank of Cerro Corero (part of the LYVC) there is a spot that ‘smokes’ occasionally. It was reported that steam has emitted from this vent in the past, but currently the spot is a small flat area covered by grasses and rocks, and shows no hydrothermal activity or deposits.

The large complex of LYVC is easily accessible along its western edge, there is a new paved road to the town of La Laguna and is about an hour and a half drive from Santiago, the capital of Veraguas province. From La Laguna the road deteriorates badly and is not drivable in the rainy season, especially October to December. Even when dry, few vehicles can navigate the road that goes to the northeast side of the complex to the village of San Jose. Accessing the eastern and southern parts of the complex is difficult, thus fewer samples were obtained from these areas.

The area surrounding LYVC is classified as pre-montane wet forest, which consists of lowland and mid-elevation rain forest species (Bush, 1992), but most of the native vegetation is gone, replaced with large plantations of Caribbean Pine covering more than 2 000 hectares (Autoridad Nacional de Panama (ANAM)), weedy grasses and farmland. A portion of the LYVC is used for farming, some for shade grown coffee, but mostly for corn, beans, rice and other crops. Most of the soils in the area are degraded and poor, and much of the land is unsuitable for growing crops and is used for grazing cattle. The valley where Media Luna is located (both the town and the cinder cone), has a much richer soil, possibly because of the young volcanic parent material, and better supports crops. Some of the moisture coming from the north over the Cordillera Central reaches this valley during the dry season, but does not reach the main volcanic complex area, which only gets moisture during the rainy season.

Figure 2 (following page). Geologic map of the La Yeguada Volcanic Complex

Geologic Map of La Yeguada Volcanic Complex



2.1 Tectonic Setting

Panama is surrounded by micro–plate boundaries; on the Pacific Ocean side the Nazca and Cocos plates are subducting beneath the Caribbean plate, and a triple junction occurs to the south of the Costa Rica/Panama border (Figure 3). The Panama Fracture Zone runs north/south, separating the Cocos plate on the west from the Nazca plate on the east. All this subducts at the Middle American trench (Morell et al, 2008). Convergence of the North America and South America plates slowly compresses the Caribbean plate, and is more pronounced along its western edge in Central America, which contributes to the zone of deformation along the northern, Caribbean coast of Panama, thus separating the Panama block from the larger Caribbean plate (Hoernle et al, 2002, Morell et al, 2008).

The Central American volcanic front ends abruptly where the subduction of the thick Cocos ridge below southern Costa Rica creates the onshore uplift of the non-volcanic Talamanca mountain range (Figure 3). East of the Cocos ridge, the Panama Fracture Zone enters the Middle America trench south of the Costa Rica/Panama border. This corresponds with onshore fracturing (Morell et al, 2008) and volcanic activity resumes with Volcán Barú in western Panama. To the east, there is another change in subduction style, due to more oblique subduction of the Nazca plate below the Panama block, leading to the mild volcanic activity and seismicity witnessed in Panama (Coates, 1997). According to Morell et al (2008) the triple junction is migrating to the southeast along the trench at the rate of 55 mm per year, and as it slowly migrates, western Panama will experience Cocos subduction similar to current activity below southern Costa Rica.

It is unclear where the exact termination of the Middle America trench is located, and how it intersects with the South America trench. The last known eruption in Panama occurred 400-500 years ago from Volcán Barú (Sherrod et al, 2007), while the most recent eruption from La Yeguada occurred approximately 32 000 years ago, and at El Valle the El Hato Ignimbrite Flow is known to be younger than 56 000 years based on stratigraphy, but likely is Holocene (<10 000 years) based on the fresh morphology in a tropical area. Compared to the active volcanic systems to the north along most of Central America, Panama has a much larger spacing between volcanic front volcanoes and a less frequent eruptive style. Therefore, most researchers consider it to be geologically separate from Central America (Carr et al., 2003, 2007).

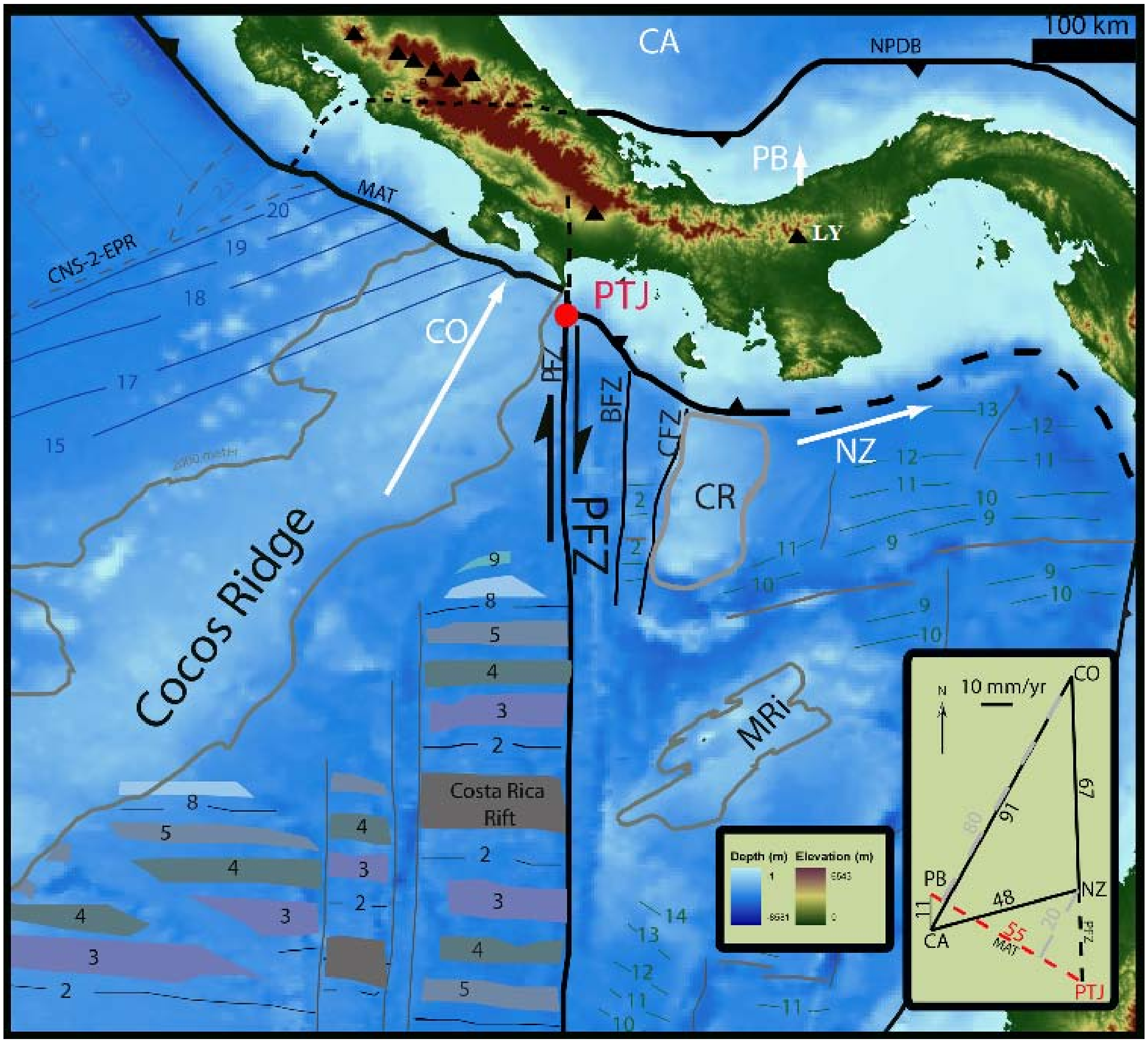


Figure 3. Regional digital elevation model of southern Central America. Black triangle on the right (LY) is La Yeguada Volcanic Complex. (Figure used with permission from K. Morell, from Morell et al (2008)). Panama Triple Junction (PTJ, red dot) at the intersection of the Cocos (CO), Nazca (NZ) and Panama block (PB), part of the Caribbean (CA) plates. PFZ = Panama Fracture Zone, NPDB = North Panama Deformed Belt, MAT = Middle America Trench. White arrows indicate plate motion vectors relative to a fixed Caribbean plate. Black triangles denote active volcanoes. Map of identified magnetic anomalies on lower plate based on data by Barckhausen et al. (2001), Lonsdale and Klitgord (1978), Lonsdale (2005), Lowrie et al. (1979), and modified after MacMillan et al. (2004). Numbers show age in millions of years based on the chron time scale of Cande and Kent (1995). BFZ = Balboa Fracture Zone, CFZ = Coiba Fracture Zone, CR = Coiba Ridge, MRi = Malpelo Ridge, CNS-2-EPR = boundary between crust originated at Galapagos Hot Spot (CNS-2, south of boundary) and EPR (East Pacific Rise) crust (north of boundary). Bathymetry supplied by the USGS GTOPO30 dataset, and topography by NASA SRTM-3 90-m DEM. Inset. Plate vector diagram after Sitchler et al. (in press), relating Cocos, Nazca, Caribbean plates, and Panama Block. Solid lines denote relative plate velocity vectors based on velocity model NNR-NUVEL-1B derived from Bird (2003), DeMets et al. (1990), Shuanggen and Zhu (2004), and Silver et al. (1990). Bold dashed lines represent the location of the Middle America Trench, and Panama Fracture Zone, respectively. The intersection

of these represents the Panama Triple Junction, which migrates to the SE along the Middle America Trench with respect to a fixed Panama Block at a rate of approx 55 mm/yr (red dashed line). Panama Block–Nazca (PB-NZ) and Panama Block–Cocos (PB-CO) convergence are shown as dotted gray lines orthogonal to the Middle America Trench. Rates are shown in mm/yr.)

2.2 Historical Record of Lake La Yeguada

Lake La Yeguada has been a continuous lake in Panama for the past 14 000 years (Coates, 1997). Only a few other long lasting lakes have been located in Central America, and have proved important for studying the effects of the last ice age and how people, animals and plants migrated across the land bridge. A lake dating back to possibly 100 000 years ago up to 8 000 before the present (BP) filled the crater of El Valle, at which time the lake drained when a crack in the crater wall opened. Pollen and phytoliths (silica nodules from plants) from the lake cores of La Yeguada and El Valle record the descent of highland species during the time of cooling of the last ice age, though no ice covered Panama. Unlike portions of the Caribbean coast in Guatemala and Belize, which were characterized by dry savannas during the last ice age, the data show that lowland Panama was continually forested during the entire period exposed by the lake cores. Changes in weather patterns and plant species are noted during the transition from the end of the last ice age (about 10 000 BP) into the present (Coates, 1997, Bush et al, 1992).

Several studies have been conducted at Lake La Yeguada (Piperno, 2003 and 1991, Cooke et al, 2003, Bush et al, 1992). In Bush et al (1992) two cores were obtained below the lake and analyzed, and the 17.5 m core dates back to 12,200 BP. Neither the cores nor samples from outcrops along the lakeshore show evidence of any volcanic products (D.Piperno personal communication). An eruption from the main part of the complex would necessarily leave a deposit in Lake La Yeguada, which lies at the foot of the western slope of Cerro Castillo. With low-level winds predominantly coming from the north, it is likely that a trace of an eruption from the Media Luna cinder cone, 10 km to the northwest, would also show up in the lake. Therefore, the La Yeguada volcanic complex has not been active for at least the past 12,200 years, which is supported by the rock ages obtained through argon analysis.

Evidence from pollen and phytolith studies show that humans have been using the land around Lake La Yeguada with slash and burn activity and planting maize, probably since 7 000 BP (Piperno, 2003). The same study shows that around 4 000 BP, the nearby land was mostly deforested, with a subsequent decrease in agricultural usage. Phytolith and pollen samples in the lake cores show that around 350 BP a fairly mature forest had regenerated (Piperno, 2003), which appears to correlate to the decline of indigenous populations following the Spanish colonization.

3. Geology of La Yeguada Volcanic Complex

Reconnaissance of the area began towards the end of 2006, collection of data and mapping started in February 2007, concentrating first in the Media Luna area, and field work was completed by March 2008.

Figure 4. La Yeguada Volcanic Complex, view looking to the southwest. Cerro Corero is the most prominent peak from this view.

3.1 Rock Sample Information and Results

Seven samples were selected for $^{40}Ar/^{39}Ar$ analysis and processed at the University of Wisconsin, Madison in the Rare Gas Lab. Units to be dated were chosen to span the age range of the complex, focusing on the youngest (Media Luna), the main dome, and adjacent deposits. The seven samples are; Media Luna, Castillo, Corero, Novillo, Picacho, the El Satro Pyroclastic Flow, and Mano de Pilon. However, the plagioclase in the Mano de Pilon sample was too altered to be dated, thus only six samples were actually processed. Four ages were obtained, they are; Media Luna (32 000 ± 15 000 years old), Castillo unit (0.357± 0.019 million years (Ma)), Picacho unit (4.83 ± 0.16 Ma), and the El Satro Pyroclastic Flow (11.26 ± 0.17 Ma) (See Appendix 3 for more information on sample results). The Novillo and Corero samples were significantly altered and did not produce reliable dates. Table 1 compares the samples from this paper to the samples analyzed by both Defant et al (1991) and Richerson (1990).

UNIT	Map code	Ar^{40}/Ar^{39} Age	K/Ar Age (Ma)*	Sample number	Lat/Long	General Description
Media Luna	**(●1, ■ a)**	32 000 ± 15 000	0.52 ± 0.08	KK220407-1 26-3-88*	N8 30 45.9 W80 53 21.2	Olivine basalt. Contains olivine, pyroxene, plagioclase, ~50% SiO^2.
El Satro Pyroclastic Flow	**(●2, ■ c)**	11.26 ± 0.17 Ma	9.73 ± 0.49	KK210208-1 11-10-88*	N8 28 31.2 W80 49 55	Rhyodacite/rhyolite welded tuff. Contains quartz, plagioclase, altered mafic minerals. ~70% SiO^2
Corero	**(●3)**	unable to date		KK200208-1 9-1-88*	N8 28 2.7 W80 49 14.8	Dacite dome rock. Contains amphibole, quartz, plagioclase, some biotite; slightly altered. 64-66% SiO^2
Novillo	**(●4)**	unable to date		KK060208-3	N8 27 23.4 W80 48 27.2	Rhyodacite/rhyolite welded tuff. Plagioclase phenocrysts, quartz. ~70% SiO^2
Picacho	**(●5, ■ d)**	4.83 ± 0.16 Ma	4.47 ± 0.23	KK060208-1 17-12-88*	N8 27 50.3 W80 47 32.8	Dacite dome rock. Contains plagioclase; amphiboles and biotites degraded; quite altered. ~65% SiO^2
Castillo (5a)	**(●6, ■ e)**	0.357± 0.019 Ma	8.73 ± 0.45	KK311007-2 16-5-88*	N8 26 44.6 W80 49 52.1	Andesite/dacite dome rock. Contains plagioclase, biotite, hornblende. ~60% SiO^2
Castillo (5b)	**(●7)**	not dated		KK040208-4	N8 26 16.8 W80 49 14.8	Rhyodacite/rhyolite welded tuff. Contains plagioclase, abundant quartz, some K feldspar. ~70% SiO2
Mano de Pilon	**(●8)**	unable to date		KK010208-4 19-7-88*	N8 29 27.3 W80 48 28.0	Andesite or dacite, lava. Most phenocrysts plagioclase; porphyritic. Deeply altered.
Esquinado	**(■ i)**		1.38 ± 0.08	23-3-88*		PL and PX microphenocrysts in GM. Has PL, AM and OX. 66.5% SiO2.*
SE of LYVC	**(■ f)**		7.15 ± 0.37	20-3-88*		Glass and PL in GM. Has CPX, OPX, PL and OX. 59.8% SiO^2.*
La Yeguada and Cañazas Formations	**(■ b)**		10.53 ± 0.54	17-21-88*		PL and PX microphenocrysts in GM. Has CPX, OPX, PL and OX. 53.5% SiO^2.*
La Yeguada and Cañazas Formations	**(■ g)**		12.72 ± 0.66	28-4-88*		Glass and PL in GM. Has CPX, PL and OX. 61.4% SiO^2.*
La Yeguada and Cañazas Formations	**(■ h)**		14.70 ± 0.84	8-1-88*		PL and PX microphenocrysts in GM. Has CPX, OPX, PL and OX. 55.8% SiO^2.*

Table 1. Summary and comparison of samples from this paper and from Richerson (1990). Map code refers to labels on Figure 2 (Geologic Map); circles are $^{40}Ar/^{39}Ar$ sample locations, squares are K/Ar sample locations. Sample number – the first number (KK_) is from this paper, 2nd number from Richerson.

*From Richerson, P.M., 1990, Petrogenesis of La Yeguada Volcanic Complex, Western Panama, Via Both Differentiationand Slab Melting: Masters Thesis. OL-olivene, CPX-clinopyroxene, OPX-orthopyroxene, PL-plagioclase, AM-amphibole, OX-Fe-Ti oxides, BT-biotite, PX-pyroxene, GM-groundmass.

Viewing the thin sections of Cerro Mano de Pilon and Cerro Picacho through the microscope, extensive alteration is evident, and both contain degraded amphibole and biotite, along with quartz and plagioclase. Picacho (4.83 ± 0.16 Ma) is a dacite, and the deeply weathered Mano de Pilon (undated) is either an andesite or dacite. Richerson (1990) calls Mano de Pilon a rhyodacitic pyroclastic deposit and notes that it appears to be Miocene because it is overlain by the El Satro Pyroclastic Flow (ESPF). Richerson

(1990) noted that it is likely that as the younger peaks came up through the older ESPF, some of the ESPF unit was transported and now sits on top of the younger dome rocks. Within the Castillo unit (Tca) two samples are clearly welded tuffs (Castillo 5b [KK040208-4] and Novillo [KK060208-3]), however there is no evidence to support that these are blocks of the ESPF. These welded tuff samples have well-preserved pyroclastic flow features and are more likely separate events, which are commonly associated with andesitic and dacitic lava flows (Cas & Wright, 1988). The Knutsen sample of Mano de Pilon is not a welded tuff, and therefore the Richerson sample may be another example of a pyroclastic flow within the unit.

Many of the rocks surrounding La Yeguada and in the greater area are Miocene volcanics, mostly at or near Tortonian (11.6 to 7.2 Ma). The Richerson K/Ar samples b, g and h (See Figure 2) belong to the La Yeguada and Canazas Formations with ages of 10.53, 12.72 and 14.7 Ma respectively. Sample f, deemed a separate unit by Richerson but not large enough to distinguish on the map, has a K/Ar age of 7.15 Ma. Five $^{40}Ar/^{39}Ar$ ages were obtained by a German group (GEOMAR); two near Santa Fe, Veraguas to the west (8.7 and 10 Ma), two in the El Cope, Cocle area to the east (12.4 and 12.5 Ma), and one just northwest of Santiago, Veraguas (20.3 Ma) (K. Hoernle personal communication). Clearly, volcanic output was more voluminous during the Miocene, with the subsequent decrease in volcanism a probable result of the shift in subduction of a hotspot track from western Panama to southern Costa Rica, beginning the uplift of southern Costa Rica around 5 Ma (Hoernle et al, 2002). The $^{40}Ar/^{39}Ar$ age for the El Satro Pyroclastic Flow is also Tortonian (11.26 Ma) and not too different from the La Yeguada and Canazas units. Figure 4 is a histogram showing the various ages obtained at and around the La Yeguada volcanic complex. It seems reasonable to assume that a larger dome existed at LYVC in the Miocene, and that the large alluvial fans and lava flows on the southern flank are likely associated with this earlier period of volcanism.

Unfortunately, the Corero sample could not be dated, as this unit appears to be the youngest part of the main dome, and has a lava flow on the northeast corner that maintains a rough looking surface texture. This is the same area where steam reportedly comes out occasionally of a small hole as mentioned in section 2. The youngest eruption in the complex is from the Media Luna cinder cone (approx. 32.0 ± 15 ka (thousand years)), which is separate from the main dome (Figure 2).

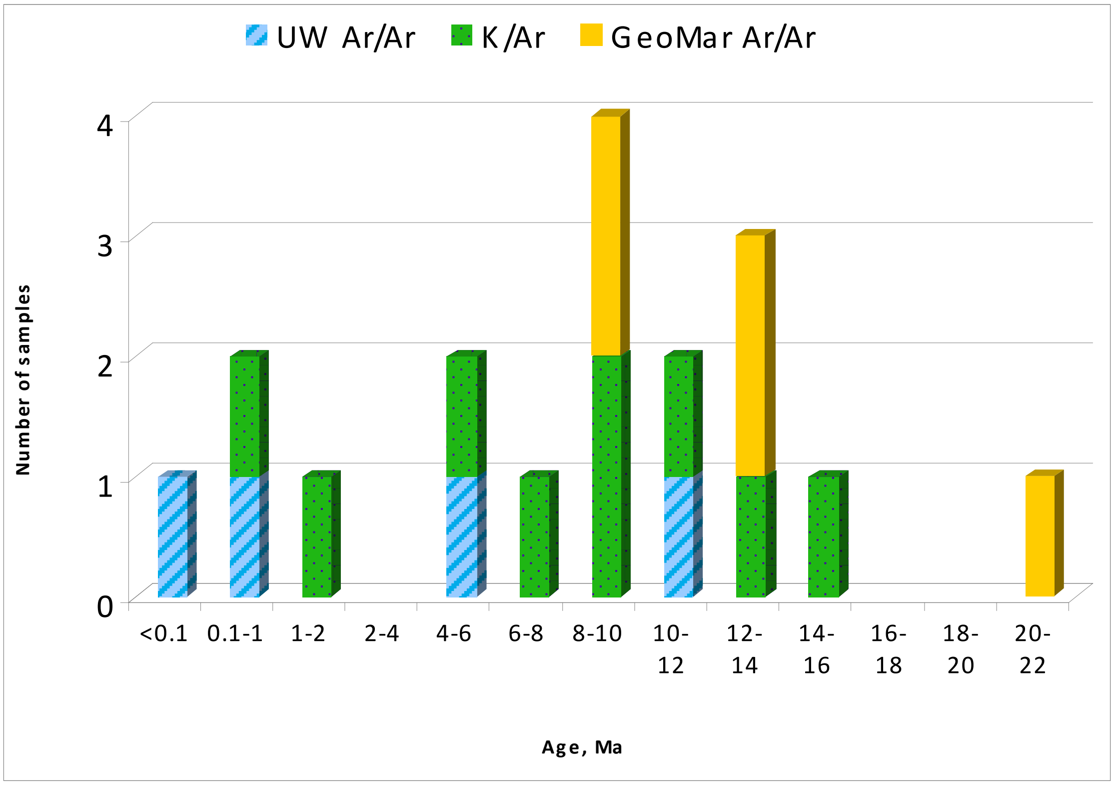


Figure 5. Histogram showing all the ages analyzed at and around the La Yeguada Volcanic Complex. UW $^{40}Ar/^{39}Ar$ are the new dates reported in this paper, analyzed at the Univ of WI, Madison by Brad Singer and Brian Jicha. K/Ar ages are from Richerson (1990), and GeoMar $^{40}Ar/^{39}Ar$ ages obtained from the German group (K. Hoernle personal communication 2009).

3.2 Geologic Map of La Yeguada Volcanic Complex

The map was created using ArcGis, based on the geologic map in both Defant et al (1991) and Richerson (1990), and used the following layers: two topographic maps, “La Yeguada” and “Gatu” from “Tommy Guardia” in Panama City; hillshade map courtesy of Instituto de Geociencias, Universidad de Panama; and the Digital Elevation Model (DEM) is from the Shuttle Radar Topography Mission. The geologic unit names are taken from Defant et al (1991) and Richerson (1990) (See Figure 2).

As noted earlier, the three peaks comprising the main volcanic center of La Yeguada are Cerro Castillo, Cerro Corero and Cerro Novillo. The opening of the crater is to the north/northwest, towards the town of El Satro. The El Satro Pyroclastic Flow (ESPF) is the largest unit and extends from the west, along the north, and to the east of the volcanic center and is much older (11.26 ± 0.17 Ma) than the three peaks (Castillo 0.357± 0.019

Ma). It is likely that this unit covered a much larger area than what is currently mapped, and differences in coverage are explained by erosion, coverage by younger rocks and incomplete mapping of the peripheries of the complex. The Lake La Yeguada sits inside this unit, and just to the south of the lake the edge of the ESPF unit is evident in the steep drop along the road south of the town of La Yeguada. Defant et al (1991) and Richerson (1990) show the portion of ESPF on the eastern side of LYVC as a debris flow; however we found no evidence of a large debris flow in this area. Most of the rock appears to be ESPF, often deeply weathered, and occasional outcrops of unconsolidated material were noted, but seemed to be small, localized occurrences.

Based on hand samples and topography, it was decided to include Novillo in the Castillo unit as in Defant et al (1991) and Richerson (1990). The La Yeguada dome includes the Castillo unit (comprised of Cerro Castillo and Cerro Novillo) and the Corero unit; the maximum width of the dome is just over 4 km, and the maximum length is about 4.5 km. Large fans come off of the dome to the south and though they may be a product of the LYVC, the morphology is distinct and an outcropping along the road south of the town of La Yeguada shows that at least a portion of this material appears to be older, more weathered lava, with re-worked volcanic sediments.

Looking at 3D images, along with the DEM and hillshade, a strong linear feature was noted and drawn in as an inferred fault on the map. It cuts across the dome, separating Cerro Castillo from Cerro Novillo and is probably contributing to the erosion seen inside the crater. Inside the crater, the rock is quite altered, few good exposures were found, and there is much sloughing of material off the rock walls. Along the trail to the top of Cerro Castillo the rocks are highly altered, and at about 1 040 m elevation there is a section of centimeter scale banding, sloping steeply downhill. This is located near the crater edge and could be a result of faulting.

3.3 Media Luna Cinder Cone

The Media Luna cinder cone and its lava flow lie 10 km to the northwest of the main La Yeguada volcanic complex (See Figure 2). The small cone is geomorphologically clearly constructional, and only rises 100 m from the valley bottom, with the top at 700 m, and has a breached opening on the western side. The lava flow breached the cinder cone and follows the Media Luna valley to the east for 2.5 km until it merges with the Rio Chitra drainage, where it spreads out slightly and heads southwest for approximately another 1.5 km. The lava flow deposit is never more than 500 m wide along its entire length. The outline of the Media Luna lava flow was delineated by walking along the contact and carrying a GPS unit, except for two short segments where the continuation of the contact was obvious. In the southwestern portion of the lava flow, in the Rio Chitra, there is a distinctive contact between the flow and an older unit, with the flow showing columnar jointing. No outcrops of lava were found on the eastern side of the cinder cone in the village of Media Luna. Instead, the valley floor contains sediments, possibly a result of damming of water behind the cone after emplacement.

Figure 6. Media Luna cinder cone; view of east side, opening from last eruption is on the west side. The village of Media Luna in foreground.

3.4 La Yeguada Stratigraphy

The town of La Yeguada lies in a relatively flat basin that has filled with volcanic sediments. A couple of outcrops in town show an approximately 2.5 m section of small to large boulders within a fine matrix, which sits unconformably on top of fine-grained sedimentary layers. An outcrop along the road just south of the town of La Yeguada (N8 25.455, W80 51.344), near the hydro-electric station, exposes a larger sequence of sedimentary layers, composed of flat-lying, distinct layers of fine, to very fine grained material. Some of this material is re-worked volcanic deposits, for example the unit below the soil horizon contains abundant altered pumice fragments. Other units appear to be fine sands and muds with probable ash content, and there is a charcoal lens 3 m below the soil horizon, with a maximum thickness of 10 cm and approximately 10 m wide. Below the charcoal, appears to be an old soil layer, with evidence of worm burrows.

3.5 Adakites

Defant et al (1991) and Richerson (1990) refer to two separate periods of volcanism; rocks belonging to the "young group" are less than 5 Ma and tend to be dacites; and the "old group" which "consists of basalts and basaltic andesites as well as andesites to rhyolites" (Richerson, 1990). For both La Yeguada and El Valle, the term adakite was applied to the young group of rocks based on chemical composition and was presumed to result from a change of style in subduction below the Panama block. However, this designation does not apply to the 32 000 year old Media Luna basalt. Other studies have shown that from 4.5 ±0.17 to 0.1 ±0.08 Ma volcanism consisted of low volume alkaline and adakitic eruptions in western Panama (Lissinna, 2006), coinciding with the ages of the younger volcanism at LYVC.

The new ages obtained from both La Yeguada and El Valle verify that there is a gap in volcanism, with an older period ending approximately 5 Ma and then re-initiating around 350 000 years ago in the case of La Yeguada, and around 100 000 years ago at El Valle. Refer to Defant et al (1991) and Richerson (1990) for a detailed discussion on the composition changes that occur between the older and younger groups of volcanism.

3.6 Magnetism

Richerson (1990) reported data on ground-level paleomagnetic polarity tests, which showed that Cerro Corero and Cerro Picacho are positively magnetized, while Cerro Castillo and Cerro Novillo are negative. At 4.83 Ma, Cerro Picacho belongs to the Sidufjall normal polarity subchron of the Gilbert Chron. However, Cerro Castillo has an age of 0.357 Ma, which puts it in the Brunhes normal polarity Chron and not during a reversed polarity event.

4. Geologic Hazards of La Yeguada Volcanic Complex

The volcanic threat of a specific volcano can be estimated by a systematic methodology as proposed by Ewert et al (2005). Using this method, the relative threat ranking of a given volcano is a product of its hazard score (including volcano type, eruption recurrence, style and frequency of eruptions, etc.) multiplied by its exposure score (humans and property at risk from a volcanic event). The hazard score is based in part on activity younger than 5 000 years. There are five threat subdivisions ranging from very high to very low. Using this system applied to Panama only Volcán Barú has demonstrable significant volcanic threat, since it is the only Panamanian volcano with known activity in the past 5 000 years and also has a fairly high exposure score.

The La Yeguada Volcanic Complex is listed on the Smithsonian Global Volcano Program as one of the three possible active volcanoes in Panama; therefore it is important to assess the hazards posed by the LYVC, since many small communities surround the complex. At LYVC, the Media Luna cinder cone is the only young deposit with an approximate age of 32 000. The hazards associated with cinder cone activity are localized and exposure score is also low. Monogenetic cones, such as Media Luna, typically do not produce more than one eruption, and it is conceivable though statistically unlikely, that another cinder cone could erupt somewhere else in the area.

Central American volcanoes tend to be fairly short lived, often no older than a couple 100, 000 years, and are characterized by bursts of activity with periods of quiescence (Escobar Wolf, 2007). The youngest obtained age at the main dome complex of LYVC is 357 000, which makes it unlikely that it will erupt again. The span of ages extending back into the Miocene suggests that the complex is the result of two or more distinct eruptive periods, or even several different collocated volcanoes. Referring to the volcanic threat analysis methodology of Ewert et al (2005), since there is no evidence for Holocene (<10 000 years) activity at the La Yeguada volcanic complex, we conclude that it is unlikely to erupt and its threat level at very low. The geothermal springs in the area seem to be very weak, and are unlikely sites for hazardous geothermal explosions**.** However, there is a serious threat posed by potential landslides due to unstable slopes composed of altered to quite altered rocks, along with the steep slopes surrounding the complex. Further work or research should focus on mapping zones most prone to mass wasting.

4.1 Geologic Hazards of other Panamanian Volcanoes

El Valle

The town of El Valle at 500 m sits inside the caldera on a flat valley floor composed of lake sediments. Of the three Quaternary volcanoes in Panama, El Valle is the easternmost volcano and is composed mostly of andesites and dacites, which spans a smaller compositional range than the rocks at La Yeguada, where there are some basalts as well as rhyolites. The most recent eruption from El Valle is the El Hato pyroclastic flow, and was likely a caldera collapsing event resulting in an ignimbrite deposit that covers approximately 300 km^2 (Hidalgo, 2007). The exact age of the El Hato deposit is unknown, however it overlies and is younger than, the 56 000 year old India Dormida dacite, but based on the preserved structures of the flow, it is likely to be Holocene in age. Because this young pyroclastic flow reached far to the south of the volcano and crossed the Pan-American Highway, and because of other units which are younger than 100,000 years, El Valle should be considered a potentially hazardous volcano.

Volcán Barú

Volcán Barú is the tallest of the three Quaternary volcanoes, at 3 374 m, and sits near the Costa Rica border in western Panama (Figure 1). Barú lies on the southern slope of the Cordillera Central, and has an impressively large dome complex that rises over 2 000 m above the populated valleys surrounding it. Spurred by a series of volcanic tremors in 2005, the Panamanian government with the help of USAID, requested assistance from the U.S. Geological Survey to provide a hazard assessment of the volcano. USGS Open-File Report 2007-1401 (Sherrod et al, 2007), is an account of their findings.

Three, perhaps four, eruptions have occurred in the past 1 600 years, and include tephra fallouts, pyroclastic flows and lahars (Sherrod et al, 2007). A large opening on the southwest side of the dome shows the pathway of a huge dome collapsing event that resulted in a large debris avalanche that crossed the current location of the Pan-American Highway, 30 km to the south. The terrain covered by the debris avalanche deposit has a distinct hummocky character. The flanks of Volcán Barú are mostly forested, with forests continuing to the north, but to the south the land is fairly densely populated, and supports a rich soil with a cool climate that is an important economic center for vegetable crops and coffee plantations, as well as cattle grazing in the lower areas. Barú has by far the most potential of the three volcanoes of renewing volcanic activity, as well as the potential to cause considerable damage, and subsequently is better monitored with several seismometers in the area.

5. Discussion

5.1 Caldera Theory

It is suggested that the La Yeguada volcanic complex lies within a caldera complex based on several observances. First is the roughly circular feature of the complex with arcuate topographic boundaries on its NE and SE margins that contain the peaks Cerro Mano de Pilon and Cerro Picacho. Second, the youngest unit (aside from the separate Media Luna cinder cone) is Castillo, forming part of the main dome complex within the caldera, and this central dome along with domes along the caldera edges mimics other known caldera settings. Third, it is common to have a large silicic eruption associated with a caldera, and here the El Satro Pyroclastic Flow at 11.26 Ma is a highly silicic welded tuff, and by far the largest unit mapped in the complex. Fourth, the Lake La Yeguada looks to lie within the moat section of the caldera, and this too is a common feature seen in other calderas.

No detailed field geologic mapping was done to substantiate the presence of a caldera, and further investigation is needed. A preliminary outline of the caldera boundary is shown on the geologic map (See Figure 2).

5.2 Other Research

This study only looked at the deposits near the LYVC and Media Luna, but there are other interesting volcanic deposits in the greater area and it would be useful to know if they are products of the LYVC or from older periods of volcanism. For example, there is an ignimbrite deposit exposed in a river channel, located south of the town of Calobre, on the road between San Francisco and Calobre, roughly 20 km to the southwest.

In his thesis, Richerson (1990) mentions two other dacitic domes that this study did not examine. One is the Montanuela dome located about 12 km to the east, and the other is the Esquinado dome, 13.5 km to the southwest. Richerson (1990) obtained a K/Ar date of 1.38 Ma for the Esquinado dome.

Several papers have referenced the following paper; [Cooke, R. 1988 “Radiocarbon Dates on Ash Layer in the Laguna Yeguada, and from Oldest Deposits in a Small Lake formed by a Basaltic Lava Flow” (Preliminary Report), Smithsonian Institution (in preparation)]. Richard Cooke from the Smithsonian Tropical Research Institute in Panama, has worked extensively in the area surrounding the LYVC and Media Luna, and met with some of the geologists that have worked in the area, but never published the paper listed above (personal communication). Apparently, this paper suggested that the youngest eruption from the Media Luna cone may be 360 ± 80 years BP (before the present), based on a dated peat layer from the bottom of a lake near the cone. The hypothesis is that the lake was created by the damming of an old river channel by the last lava flow, and that this peat layer approximates the date of the last eruption. There is no evidence to support this hypothesis, and in fact is extremely unlikely to be true given both the $^{40}Ar/^{39}Ar$ and K/Ar ages, and hopefully this date will stop being cited as a possible eruption date for the Media Luna cone.

6. Conclusions

Due to the increased precision of the $^{40}Ar/^{39}Ar$ dating method, the four new ages at the La Yeguada Volcanic Complex increase our understanding of its volcanic history, and allow for an assessment of the hazard potential of the complex. The most recent eruption at La Yeguada volcanic complex occurred approximately 32 000 years ago at the Media Luna cinder cone, while the most recent eruption at the main part of the dome occurred 0.357 Ma. We conclude that the most likely geologic hazard at La Yeguada would be from landslides, and that an eruption in the near future is extremely unlikely. Looking at the three Quaternary volcanic centers in Panama and their potential hazards, Volcán Barú presents a moderate threat, El Valle a possible threat, and La Yeguada is not a threat.

At this time, the potential hazards for the communities in the area surrounding the complex are low. Subduction still occurs beneath Panama and therefore the potential exists for renewed activity in the area. It is recommended to install a seismometer, or ideally several, to understand the level of present earthquake activity and then be able to note if activity increases in the future. Residents in El Satro and La Laguna report that they have felt small earth movements in the past.

In the past few years, the network of seismometers has increased throughout Panama, deployed by the Geophysics department at the Universidad de Panama. Also, the Observatorio Sismico del Occidente de Panama run by Angel Rodriguez, works with the Civil Protection Agency (SINAPROC) in Panama to install, maintain and update more seismometers in the country.

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Appendix 1: Sources for the geologic map (Figure 2)

Two topographic maps by the Instituto Geográfico Nacional; (1) Hoja 4041 III serie E762, La Yeguada, Edición 2-IGNTG, Panamá 1:50,000, and (2) Hoja 4041 IV Serie E762, Gatú, Edición 1-IGNTG, Panamá 1:50,000.

Hillshade map courtesy of Universidad de Panamá, Departamento de Geofisica, Eduardo Camacho.

Digital Elevation Model from Shuttle Radar Topography Mission (SRTM), US Geological Survey 2004. Source for this data set was the Global Land Cover Facility, www.landcover.org.

Potassium/Argon (K/Ar) dates from Richerson (1990) and Defant et al (1991).

Appendix 2: Permission for the use of Figure 3 - Regional digital elevation model of southern Central America, from Kristin Morell.

Re: Figure 1 permission

From: **Kristin Morell** (kmorell@geosc.psu.edu)
Sent: Thu 4/09/09 2:06 PM
To: Karinne Knutsen (karinne_knutsen@hotmail.com)
Hi Karinne, This shouldn't be a problem at all. I even have a version saved called "Figure 1 simple". What type of format would you like it in?
Cheers,
Kristin
On Apr 9, 2009, at 3:51 PM, Karinne Knutsen wrote:

Hi Kristin!
I would like to know if it's possible to get permission to use one of the figures from the your paper:
"Inner forearc response to subduction of the Panama Fracture Zone, southern Central America". I cite your paper in my report. Originally I was using a different figure to show the tectonic setting but I really like your figure 1, but wonder if you have a more simple version. I don't need the 2 boxes overlain on the landmass (figure 2 and FCTB).
Karinne Knutsen

Appendix 3: Summary of $^{40}Ar/^{39}Ar$ Experiments. Analysis courtesy of University of Wisconsin, Madison through Brad Singer and Brian Jicha.

Summary of $^{40}Ar/^{39}Ar$ Experiments

				Weighted Mean Analysis				Isochron Analysis		
Sample	Experiment	Material	K/Ca total	^{39}Ar %	MSWD	Age (Ma) ± 2 σ	N	$^{40}Ar/^{36}Ar_i$ ± 2 σ	MSWD	Age (Ma) ± 2 σ
Castillo	UW75E51†	biotite	20.547	93.1	1.08	**0.357 ± 0.019**	9 of 10	299.3 ± 5.3	0.93	0.322 ± 0.049
Picacho	UW74B15‡	plagioclase	0.039	100.0	0.71	**4.83 ± 0.16**	10 of 10	296.0 ± 2.2	0.77	4.80 ± 0.20
ESPF	UW74B16‡	plagioclase	0.123	100.0	0.41	**11.26 ± 0.17**	10 of 10	296.0 ± 2.6	0.44	11.13 ± 0.79

All ages calculated using the decay constants of Steiger and Jäger ($\lambda_{40K} = 5.543 \times 10^{-10}$ yr^{-1})
† J-value calculated relative to 28.02 Ma for the Fish Canyon sanidine
‡ J-value calculated relative to 28.34 Ma for the Taylor Creek sanidine
Age in **bold** is preferred

			Total fusion				Isochron			Plateau
Sample	Material	K/Ca total	Age (ka) ± 2 σ	N	$^{40}Ar/^{36}Ar_i$ ± 2 σ	MSWD	Age (ka) ± 2 σ	^{39}Ar %	MSWD	Age (ka) ± 2 σ
Media Luna	groundmass	0.45	56.9 ± 36.8	8 of 8	296.7 ± 2.9	0.67	18.0 ± 17.0	100.0	0.66	37.2 ± 20.6
	groundmass	0.42	27.0 ± 25.1	7 of 8	296.1 ± 2.3	0.18	12.2 ± 23.5	99.9	0.19	25.0 ± 23.4
							Weighted mean plateau age from 2 experiments:			**32 ± 15**

J-value calculated relative to 28.201 Ma for the Fish Canyon sanidine (Kuiper et al., 2008)
Age in **bold** is preferred